Evidence for a 20° tilting of the Earth's rotation axis 110 millions years ago

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Abstract
True polar wander (TPW), the shift of the Earth's rotation axis with respect to the entire globe, is most probably due to mass redistribution in the Earth's mantle as a result of convection. Using a new rigorously selected palaeomagnetic database gathering only directions obtained from magmatic rocks, we find that TPW has been clearly intermittent over the last 200 Ma with two long periods of strict standstill from the present to 80 Ma and from approximately 150 to 200 Ma. A single period of shifting is observed, between 80 and about 150 Ma ago. This period culminates around 110 Ma ago in an 20° abrupt tilting during which an angular speed exceeding 5°/Ma (0.5m/yr) may have been reached. Assuming that the time-averaged geomagnetic field is axial, our results indicate that the changes in the position of the rotation axis, and therefore in the inertia tensor of the Earth are intermittent. We suggest that a major reorganization of the mass distribution in the Earth's mantle occurred in the Lower Cretaceous. This event, concomitant with plume hyperactivity at the Earth's surface and probable drastic changes at the core/mantle boundary attested by the inhibition of geomagnetic reversals, suggests unmixing of upper and lower mantle by avalanching of upper mantle material down to the core/mantle boundary. The astonishingly strict stability of the time-averaged position of the rotation axis before and after this episode of shifting implies the existence of some steady convection which does not modify the large scale distribution of mass within the mantle. Given the intermittence of mantle avalanching, we suggest that these long periods of stability correspond to the temporary reestablishment of a basically two-layered convection system within the mantle.

Keywords: polar wandering; rotation; Earth; paleomagnetism; mantle; convection

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1. Introduction

True polar wander (TPW), the shift of the Earth's rotation axis with respect to the entire globe over geological time, is a phenomenon of particular interest for studying past geodynamic events originating in the Earth's deep interior. TPW is interpreted as a response to mass redistribution in the entire Earth's system [1]. The effects of climatic changes and lithospheric plate movements at the Earth's surface on the spin axis position are still a matter of debate [2-4] and, in all cases, correspond to short time-constants. In contrast, there is little doubt that mantle convection should control the position of the Earth’s rotation axis through the slow mass redistribution due to continuous subduction and advection of density heterogeneities [6,7] or, occasionally, large upwelling of mantle plumes (e.g. “superplume” [8]) or sudden avalanches of upper mantle material [9].

The TPW paths for the last 200 Ma so far proposed were obtained by combining palaeomagnetic data of magmatic or sedimentary origin [10-12], and sometimes [13] magnetic data from seamounts. These paths show in general some obvious similarities, but there is no agreement regarding the number, date and duration of the periods of pole standstill and pole shifting which seem to have succeeded one another since Jurassic. Most probably, the differences between the TPW paths are due to differences in the database used [12,14]. In the hope of producing a more reliable TPW path, we constituted a new database restricted to palaeomagnetic directions extracted from rocks whose primary remanence is a thermoremanent magnetization (TRM). Primary TRM is carried by magmatic rocks, either extrusive or intrusive. This remanence has two qualities of great importance in the present context: (i) it records faithfully the Earth's field direction, with a precision probably better than 2° [15], and (ii) it is acquired just when the rock forms (by cooling down to ambient temperature); in other words, TRM has the very same age as the rock carrying it. These two qualities are not simultaneously present for the primary remanences typically found in sedimentary rocks, which are either of detrital or chemical origin. It is well known that detrital remanence can record incorrectly the field direction while the chemical remanence has a generally unknown date of acquisition which can sometimes largely postdate sedimentation. In addition to palaeomagnetic reliability, another advantage of magmatic rocks is that their numerical age can be obtained by direct isotopic dating, which allows a more direct timing of TPW episodes.

2. Database and analysis

The selected palaeomagnetic data are restricted to magmatic units of basaltic or andesitic composition. Data from more acidic extrusives such as phonolites, trachytes, dacites, rhyolites and their intrusive equivalents (e. g., granites) were rejected because, from the personal experience of one of us (M. P.), they sometimes provide quite incorrect paleofield directions. Directions of magnetization of seamounts were not considered because this magnetization, calculated from the associated magnetic anomaly, is the sum of the primary remanence plus a viscous induced magnetization, much larger than the viscous remanent magnetization [16] and always directed along the present field direction. In order to constitute a database of relatively similar geographic extent over the last 200 Ma, we considered only data obtained from the main lithospheric plates whose positions with respect to each other are relatively well known for most of this period: Africa, Eurasia, North and South America, Australia and East Antarctica. For each of these plates, the palaeomagnetic data from areas known or suspected to have been mobile over the last 200 Ma (e.g. Iberia, India, South-Eastern Asia, American belts, Colorado plateau) were not considered. Because of the quiet tectonic environment of the selected sites, no tilt correction was applied except for 10 of them. Our selection was carried out from the IAGA palaeomagnetic database [17], as updated on July 1997, in which no Soviet data are included. We added a few African data (Madagascar, Mauritania) listed in another compilation [18]. We returned to the original publication in case of doubts about the geologic or palaeomagnetic data.

Our palaeomagnetic selection criteria were more severe than in prior [12,18]. We accepted only individual poles calculated from a minimum of 10 sites, with at least 5 samples per site. Samples should have been progressively demagnetized, the Fisher dispersion parameter K larger than 10, and the 95% uncertainty about the average direction less than 15°. Because the number of sampling sites, even when large, does not ensure that several distinct records of the field are included in the calculated mean direction, an additional criterion was devised to retain only the average directions for which paleosecular variation has been somewhat minimized. As the dispersion parameter K_{sv} due to secular variation is empirically found (when calculated from a representative data set) not to exceed 100 (more often 50), we rejected all directions with K larger than 100. Larger K are generally indicative of a field recording restricted to a short time-interval. Due to secular variation, a site-averaged direction can then be well away from the true time-averaged field direction.

Virtual geomagnetic poles (VGP) were calculated for three different configurations of the geomagnetic field. Model 1 assumes that the time-averaged field is purely dipolar. Model 2 assumes that the averaged field includes a dipolar (g^0_1) plus quadrupolar (g^0_2) components with a g^0_2/g^0_1 ratio constant over the last 200 Ma and equal to 0.05, as suggested by the most recent analyses [19,20] of the palaeomagnetic data obtained from volcanic rocks less than 5 Ma old. Model 3, simplified from Livermore et al. [13], assumes a g^0_2/g^0_1 ratio equal to +0.05 from the present to 65 Ma and -0.08 from 65 to 200 Ma.

Each pole was rotated according to the geographic location of the site with respect to the hot spot reference frame at the time of emplacement of the rock unit. This correction was made in two steps. First each plate was replaced to its past position with respect to Africa (kept in its present position), and the pole was rotated accordingly, using the most recent global plate reconstruction known to us [21]. A second rotation was applied to account for the motion of the African plate with respect to Atlantic and Indian Ocean hotspot tracks as recently revised by Müller et al. [22]. To account for possible between-hotspots relative movements, this rotation was deduced from the best fit of dated hotspots tracks from the North American, South American, African, and Indian-Australian plates considered in concert. The hotspot tracks on the Pacific plate were not be used because the exact movement of this plate with respect to the others remains a matter of debate, especially during Mesozoic. This is for the same reason that the paleomagnetic data obtained from this plate are not considered here. For upper Cenozoic, this reconstruction is based upon six hotspots but the number of usable hotspots progressively diminishes as one goes back in time. Only two hotspots (Tristan Da Cunha and New England) are used before 84 Ma ago. Since the reconstruction of Müller et al. [22] extends only back to anomaly M-10 (dated at 130.0 Ma), the displacement of Africa with respect to the hotspot frame between 130 to 200 Ma was taken from the previous work of Morgan [23]. In contrast to some previous studies [e.g., 13] none of the 118 rotated poles is omitted in the analysis of data presented below.

3. Polar movement

The positions of the rotated individual poles, calculated assuming a pure dipole field, are shown on Fig. 1 and average positions are listed in Table 1 for various, non-overlapping time intervals. The pole positions obtained from the magmatic database lie in general within some 10° of the TPW paths obtained by Livermore et al. [13] or, more recently, by Besse and Courtillot [12]. However, as shown in Fig. 2b, the present TPW path differs significantly from that proposed in [12]. The most important difference is the marked intermittence of the pole movement documented by the magmatic database. The more progressive pole displacement found by Besse and Courtillot is probably an artifact mainly due to their use of overlapping time intervals to compute the mean position of consecutive poles. The present data clearly show that two long periods of strict pole standstill (between 0-80 Ma and, approximately, 140-200 Ma) occurred over the past 200 Ma. The pole standstill is strictly verified for these two periods even when they are subdivided into (non-overlapping) time intervals as short as 10 Ma. In spite of the small number of data available in many of these intervals (Fig. 3a), the 10Mr-pole positions are well clustered (angular standard deviation *s* less than 4°) and does not show any evidence of progressive change with time (Fig. 2b). A single period of pole shift is documented which culminates around 110 Ma ago in a rapid deviation amounting to 20°.

The best documented (75 poles) period of standstill occurs from the present to 80 Ma. The four non-overlapping time-intervals listed in Table 1 all provide mean poles less than 3° from each other which easily pass the F test of Watson [24] for a common mean. The mean pole position obtained for the present to 80 Ma standstill is precise (α_{95}=1.2°) and slightly, but significantly, different (4°) from the actual rotation axis of the Earth. This difference is already clearly documented by the mean pole of the time-interval from the present to 10 Ma. Within this interval itself, most of the data in fact come from magmatic units with ages equal to or less than 2 Ma. In contrast to Livermore et al. [25], we find that even the youngest mean pole we could calculate with reasonable accuracy from our data (present to 2 Ma) differs from the present rotation axis. This conclusion remains true if a quadrupole component is added to the dipole (Fig. 2a). This result indicates that the deviation of the mean 0-80 Ma global paleomagnetic pole from the present pole of rotation is not an artifact due to the combined effect of a quadrupole term and the uneven longitudinal distribution of the paleomagnetic sites (no Pacific data).

The second period of standstill (140-200 Ma) is not so well documented (23 poles). However, the mean poles computed after subdividing this period into two consecutive time-intervals (Table 1) also pass the Watson test. Thus there is no evidence for a pole shift over this entire period.

The period of pole shifting can begin in fact between 140 and 160 Ma ago (Fig. 1). This uncertainty is due to the absence of poles in this interval (Fig. 3), excepting one dated at 158±8 Ma which exhibits a pre-shifting direction. The mean poles of the nominal 140-175 Ma and 110-140 Ma intervals differ by 13° (Table 1) and, as could be expected, they fail the Watson test for a common mean. Another difference is observed between these two groups of poles: the dispersion parameter (*K*) increases by a factor of two (from 74 to 145) from the oldest to the youngest interval. A value of *K* around 150 or above is typical for all the time intervals younger than 140 Ma. This rather small dispersion reflects probably mainly palaeomagnetic uncertainties, which are in part due to the incomplete elimination of palaeosecular variation effects upon individual pole positions. The absence of a significant and progressive increase in dispersion (decrease in *K*) for the rotated palaeomagnetic poles as age increases suggests that the uncertainties due to plate reconstruction do not affect notably our data until 140 Ma. The large increase in dispersion observed prior to 140 Ma is probably due to larger uncertainties in relative plate motions for older times. Because the age of 130 Ma corresponds to the change from the hotspot reference frame of Müller et al. [22] to that of Morgan [23], one may wonder if the 13° change in the average pole position between the 140-175 Ma and 110-140 Ma intervals does not simply reflect a discrepancy between these two frames. We checked this possibility by comparing the two average pole positions for the 110-140 Ma interval calculated using the rotations of Africa at 118-120 Ma as proposed by these two distinct reference frames. The difference between the averages of the rotated pole positions was found to be only 3°, which indicates that the observed shift of the palaeomagnetic pole position largely exceeds uncertainties about the relative orientation of the two hotspot reference frames.

The period of pole shifting seems to end around 80 Ma ago, as can be seen on Fig. 1. The mean poles of the 80-110 Ma interval and that of the 50-80 Ma interval (which marks the beginning of the most recent standstill period) differ by about 10° (Table 1) and fail the Watson test for a common mean. Although the dispersion parameter K for the 80-110 Ma interval is large, the mean pole has to be considered with some caution because of the small number of individual poles, and the fact that most of them come from a single plate (Africa).

The most conspicuous feature of the TPW path obtained from the magmatic dataset is the large and rapid deviation in pole position which occurs between the 140-110 Ma and the 110-80 Ma intervals and amounts to 18±5°. The date and duration of this event can be better evaluated from Fig. 3b which shows the cumulative angular deviation of the pole positions for consecutive and non-overlapping 10 Ma-width intervals with the zero set at the position of the youngest pole P_1 (recent to 80 Ma pole). No data is available from the intervals 140-150 and 150-160 Ma which contain zero or one pole (see above), respectively. The consecutive angular deviations were calculated along the great circles drawn from P_1 to P_2 (80-110 Ma pole) for data less than 110 Ma old, P_2 to P_3 (110-140 Ma pole) for data between 110 and 140 Ma old, and P_3 to P_4 (140-200 Ma pole) for data between 140 and 200 Ma old. In spite of the dispersion due to the small number of poles in several intervals (Fig. 3a), the jump in the pole position around 110 Ma ago is clearly seen. Two sets of individual palaeomagnetic poles obtained from several plates and dated around 98/101 and 118/119 Ma firmly bracket this shift. This suggests a shift age at 110±10 Ma, and a minimum rate of angular change of 1°/Ma (0.1m/yr). However, a narrower bracketing of the shift can be obtained if one examines in detail the rather dense palaeomagnetic recording of the time period around 110 Ma which seems to be provided by the South African kimberlites [26]. According to these data, the jump in the pole position would have occurred between 114 and 118 Ma, which suggests a minimum speed of 5°/Ma (0.5m/yr).

The results described above were found not to be significantly dependent upon the field model used. As an example, Fig. 2a compares the four main pole positions obtained with model 1 (presented above) and model 3. The differences vary from 0.2° (for pole P_1) to 2.8° (for pole P_4) and can therefore be neglected. The use of model 3, which is supposed to take into account the change with time of the g^0_2/g^0_1 ratio of the time-averaged field [13], should result in a significant increase of the dispersion parameter K for each time interval. Instead, erratic changes in K are observed. Clearly, as previously pointed out [12], the set of palaeomagnetic data presently available is insufficient to determine unambiguously the possible changes of the g^0_2/g^0_1 ratio with time before a few Ma.

4. Discussion

Assuming that the time-averaged geomagnetic field is axisymmetric, the results presented above describe a displacement of the Earth's rotation axis. Strictly speaking, the shift evidenced here is relative to the lithosphere and the hotspot frame attached to the mantle of the Atlantic/Indian hemisphere. In practice however this displacement can be considered with a good approximation as being relative to the entire mantle of the Earth. The possible relative motion between the Pacific and the Indo-Atlantic hotspots, generally attributed to the advection of plumes by mantle flow [27], might have speeds of 1-3cm/yr [28, 29, 30], which is one order of magnitude less than the speed of the pole shift reported here. Thus the pole tilting measured from the Indo-Atlantic hotspot frame can reasonably be used to describe the polar movement with respect to the entire the Earth, including the Pacific hemisphere. Interestingly, a rapid TPW event might have been recorded by some Pacific seamounts ranging in ages from 80 to 90 Ma [31].

In this context, three main questions arise from our results: Why is the present rotation axis different from the recent time averaged-rotation axis? How can the time averaged-rotation axis be strictly locked up for a duration of the order of 100 Ma ? What is (are) the cause(s) of the rapid tilting observed to occur around 110 Ma?

The rotation axis of the Earth tends to follow any shift of the axis of maximum inertia of the Earth with a time-lag depending upon the speed of reorientation of the equatorial hydrostatic bulge [1,5]. Increasing the average mantle viscosity (more precisely the lower mantle viscosity which is very poorly constrained) increases the characteristic time of reorientation. The time of adjustment of the bulge can then exceed a few Ma [32] and reach 10-20 Ma for a model with a viscosity ratio VR=30 between lower and upper mantle [33]. Plate motions result in negligible changes in the inertia tensor [3] but the vertical displacement or loading of lithosphere can significantly modify the position of the 'instantaneous' rotation axis [2,4]. However, since isostasy tends to cancel the inertia anomaly over characteristic times of the order of a few tens of thousands years, these shifts are transient. They result in a wandering of the 'instantaneous' rotation axis which has no effect on the position of the rotation axis when averaged over a few Ma or more. In contrast, mantle convection correspond to time constants long enough for resulting in a shifting of the rotation axis which can in principle be determined by paleomagnetic means.

The 4° difference found here between the positions of the actual rotation axis and that of the averaged pole over the last 80 Ma probably results from the different significance of these two axes. The actual rotation axis is the mean pole position over the last 100 yr. Being an 'instantaneous' pole, it is affected by the transient modifications of the inertia tensor of the Earth which have been induced recently by local lithospheric uplift or loading, in particular glaciation/deglaciation. Thus we believe that the difference between the position of these two axes is due to the wandering of the instantaneous pole around its time-averaged position. If we are right, this is the latter position of the rotation axis which has to be taken into account for analyzing geological or paleoclimatologic data, even for recent periods of time.

Over the last 200 Ma, the succession of periods of rapid shifting and long periods of strict standstill of the Earth's axis suggests that the changes in the inertia tensor are intermittent when time constants larger than 10 Ma are considered. This behavior is not easy to explain. There is of course no doubt that mantle convection has been at work over the last 80 Ma. Still, no changes in the inertia tensor is documented by the paleomagnetic data. This stability contradicts recent calculations of the change in the orientation of the maximum inertia axis of the Earth over the last 80 Ma deduced from convection models. Assuming that mass redistribution within the mantle is due either simply to slab subduction [6] or to a more complex mantle convection [7], these models predict that a slow shifting exceeding palaeomagnetic uncertainties would have occurred. There are obvious first-order differences between the observed and calculated movement of the rotation axis (Fig. 3b). At this point, it must be remembered that a severe weakness of these Earth mantle models is that the present day geoid provides a principal inertia axis some 20° away from the present pole of rotation [34]. This discrepancy requires adding C_{21} and S_{21} terms to the spherical harmonics of the gravity potential in order to obtain a present day axis of maximum inertia for the non-rotating Earth axis coincident with the present rotation axis [6,7]. These artificially added terms correspond to an angular deviation of the axis which is of the order of magnitude of the displacement substantiated by palaeomagnetic data. This suggests that only the general trend of the change in pole position obtained from these models is significant and that some doubts exist regarding the geophysical meaning of the calculation, even for the youngest ages.

The stability of the Earth's rotation axis over the last 80 Ma indicates either that mantle convection or slab subduction did not significantly modify the large-scale mass distribution within the mantle, contrary to model predictions [6,7], or that the viscosity of the lower mantle is much larger than commonly assumed. If we now turn to the shift which occurred around 110 Ma ago at a rate of a few degrees per Ma, the results Richards et al.'s [6] suggest that the relative viscosity ratios between lower and upper mantle should not have exceeded a few tens to allow such rapid changes. This means that the stability of the rotation axis cannot be explained by a very large viscosity of the lower mantle but rather by a long-term stability of the large-scale distribution of the main density anomalies within the mantle, in spite of convection. This stability can result in part from the control of the large-scale organization of mantle flow by the configuration of lithospheric plates at the Earth's surface [35,36] which is changing only slowly. Moreover, in a layered mantle with phase change at the interface, mantle flow is limited in extension and the vertical displacement of cooler or warmer material is blocked near the interface, where isostatic compensation rapidly cancel the mass anomaly [37]. Thus it seems reasonable to assume that the periods of strict standstill of the Earth’s rotation axis correspond to a two-layers convection, with only local mixings between the upper and lower mantle. Even if some of the slabs eventually cross the 670 km endothermic interface, it is conceivable that the net change of the Earth’s inertia tensor is negligible when the effects of these multiple downwellings of rather small volume (and those of their counterpart upwellings) are integrated over the whole mantle for time constants of tens of Ma.

In contrast to these periods of basically two-layered mantle convection, huge upwellings and downwellings of mantle material through the entire mantle thickness are probably the cause of the pole shift observed here between 80 and approximately 150 Ma ago with rates possibly greater than 5°/Ma. Mantle plume production of oceanic plateaus, seamount chains and continental flood basalts reaches a prominent maximum between 75 and 125 Ma ago [8], which coincides approximately with the whole period of shifting of the Earth rotation axis. This observation leads us to believe that the shifting of the rotation axis is somehow related to the hyperactivity of mantle plumes around the mid-Cretaceous. In the model of Larson and Olson [8], plumes erupt from the D" seismic layer, at least a few Ma and at most a few tens of Ma before the onset of the increase of hot spot activity at the Earth's surface. In order to explain that the shift of the rotation axis started a few tens of Ma before the increase in plume production, we have to assume a transit time of the order of a few tens of Ma, which, in this model, implies that the material is transported by newly formed diapirs. An attractive alternative model of mass redistribution is the occurrence of huge avalanches of upper mantle material down to the core/mantle boundary, which in return produces very buoyant plumes rising in particular from that boundary [9, 38]. In this model, the change of the inertia tensor is expected to precede the enhancement of mantle plume production at the Earth's surface.

Another major geophysical event occurred close to the beginning of the 150-80 Ma interval: the inhibition of geomagnetic reversals, which can be dated around 130 Ma [39]. The quasi-simultaneous occurrence during this period of unusually huge plume productions at the surface of the Earth, mass redistribution within the mantle attested by the shifting of the rotation axis, and changes in the reversal frequency presumably due to modifications at the CMB, strongly favors single-layer convection. According to the superplume model [8], the modification of the inertia tensor is concomitant with a change in the CMB conditions which, in turn, is supposed to modify immediately the reversal frequency of the geodynamo [8,39]. On the contrary, in the avalanching model the change of the inertia tensor has to precede the geomagnetic changes by a duration corresponding to the time of transit of the avalanche from the 670 km interface to the core-mantle boundary. According to the above discussion, the beginning of the shifting of the rotation axis occurred at 150±10 Ma. The difference with the date of the inhibition of geomagnetic reversals is 20 Myr, which is comparable to the magnitude of the transit time computed for a model with a viscosity contrast of 30 between the upper and the lower mantle [38]. Thus the avalanching model seems in better agreement with the whole paleomagnetic data.

Whichever is the correct model, the quasi simultaneous occurrence around 110 Ma of hudge plume productions at the surface of the Earth, mass redistribution within the mantle, and changes in the reversal frequency presumably due to modifications at the core mantle boundary, strongly favors a single-layer convecting system. The change in the direction of the pole shift observed around 125±15 Ma (Fig. 2) suggests that the mass redistribution which occurred within the mantle between 150 and 80 Ma was a complex phenomenon. It seem however that the largest plume features built during this period were emitted within a restricted area corresponding to low- to mid- Southern latitudes and longitudes between 60 and 280°E [22, 29]. In contrast, the Atlantic region is rather quiet. In particular, no change between the relative position of the New England and Tristan Da Cuhna hotspots occurred during the interval 124-90 Ma [41]. This suggests that avalanching remained somewhat laterally confined within a South Indo-Pacific region.

5. Conclusions

From a rigorously selected paleomagnetic database gathering only directions recorded as thermoremanent magnetizations, we observe a clearly intermittent shifting of the Earth's rotation axis over the last 200 Ma. Long periods of strict standstill occur with duration of the order of 100 Ma. This astonishing stability can be assigned to 'quiet periods' of steady convection during which no major mass redistribution occurs within the mantle. We suggest that this stability of the rotation axis correspond to a two-layers convection system, in which no avalanching occurs although some descending slabs can presumably cross the 670 km boundary. The single episode of shifting which is observed (from 80 to about 150 Ma) indicates that a reorganization of the mass distribution in the Earth's mantle occurred in the Lower Cretaceous. This shifting episode is concomitant with a plume hyperactivity at the Earth's surface and an inhibition of reversal frequency probably due to a major change at the core/mantle boundary. This suggests that the shifting episode is due to single-layered convection within the mantle, possibly due to avalanches of upper mantle material. This interpretation agrees with the fact that the change in inertia tensor precedes the change in reversal frequency by some 20 Ma. According to our interpretation of paleomagnetic data, the avalanching process in the mantle lasted for about 70 Ma.

It can be expected that similar jumps of the Earth's rotation axis have occurred repeatedly in older times. The possibility of rapid jumps reaching 90° is theoretically founded [1,33] and such an event was suggested to have occurred during Early Cambrian [42] as a result of inertial interchange. Unfortunately, the occurrence of rapid TPW events during Paleozoic or Proterozoic cannot be rigorously demonstrated because of the scarcity of reliable palaeomagnetic data, the large uncertainties about ages, and, more fundamentally, the absence of independent (non-palaeomagnetic) constraints about relative plate movements and geological markers of mantle reference frame. However our results lend support to the idea that the very rapid apparent polar wandering sometimes observed during these older periods [42,43,44] may be indicative of changes in the inertia tensor of the Earth rather than rapid plate movements.

6. Acknowledgements

This work could not have been carried out without the easy access to paleomagnetic data provided by the IAGA paleomagnetic database (http://dragon.ngu.no/palmag/paleomag.htm) initiated by Mike McElhinny and J. Lock. We also thank Yanick Ricard and Philippe Machetel for stimulating discussions about the geophysical implications of true polar wander, Jean Besse and Michel Westphal for their help at the onset of this study, and Peter Weiler for his careful check of the English style of this paper. The constructive reviews of Joe Kirschvink, Yanick Ricard and Will Sager were particularly appreciated. This is contribution number 218 of CNRS-INSU project ' Intérieur de la Terre '.

7. References

[1] Goldreich P. & Toomre A., Some remarks on Polar Wandering. J. Geophys. Res, 74 (1962) 555-2567.
[2] Sabadini R., Yuen D. A. & Boschi E., Polar wandering and the forced responses of a rotating, multilayered viscoelastic planet. J. Geophys. Res., 87 (1982) 2885-2903.
[3] Dickman S. R., Continental drift and true polar wandering. Geophys. J. R. astr. Soc, 57 (1979) 41-50.
[4] Gordon R. G., Plate motions, crustal and lithospheric mobility, and paleomagnetism : prospective viewpoint. J. Geophys. Res, 100 (1995) 24367-24392.
[5] Gordon R. G., Wandering why. Nature, 387 (1997) 131-133.
[6] Richards M. A., Ricard Y., Lithgow-Bertelloni C., Spada G. & Sabadini R., An explanation for Earth's long-term rotational stability. Science, 275 (1997) 372-375.
[7] Steinberger B. & O'Connel R. J., Changes of Earth's rotation axis owing to advection of mantle density heterogeneities. Nature, 387 (1997) 169-173.
[8] Larson R. L. & Olson P., Mantle plumes control magnetic reversal frequency. Earth Planet. Sci. Lett., 107 (1991) 437-447.
[9] Machetel P. & Weber P., Intermittent layered convection in a model mantle with an endothermic phase change at 670 km. Nature, 350 (1991) 55-57.
[10] Morgan W. J., Hotspot tracks and the opening of the Atlantic and Indian Oceans. In: C. Emiliani (Editor), The Sea 7, Wiley, N. Y., 13 (1981) 443-487.
[11] Andrews J. A., True Polar Wander : An analysis of Cenozoic and Mesozoic paleomagnetic poles. J. Geophys. Res., 90 (1985) 7737-7750.
[12] Besse J. & Courtillot V., Revised and synthetic apparent polar wander paths of the African, Eurasian, North American and Indian Plates, and True Polar Wander since 200 Ma. J. Geophys. Res., 96 (1991) 4029-4050.
[13] Livermore R. A., Vine F. J. & Smith A. G., Plate motions and the geomagnetic field, II, Jurassic to Tertiary. Geophys. J. R. Astron. Soc., 79 (1984) 939-961.
[14] Harrison C. G. A. & Lindh T., A polar wandering curve for North america during the Mesozoic and Cenozoic. J. Geophys. Res., 87 (1982) 1903-1920.
[15] Coe R. S., The effect of shape anisotropy on TRM direction. Geophys. J. R. astr. Soc., 56 (1979) 369-383.
[16] Plessard C. & Prévot M., Magnetic viscosity of submarine basalts, Deep Sea Drilling Project, leg 37. In: Init. Rep. D.S.D.P., 37 (1977) 503-506.
[17] McElhinny M. & Lock J., IAGA palaeomagnetic database, vers. 3.3 (1997).
[18] Beck F., Courbes de dérive des pôles du Permien à l'actuel pour les continents péri-atlantiques et indiens : confrontation avec les reconstructions paléomagnétiques. Ph. D., Univ. Strasbourg (1994) 253 p.
[19] Johnson C. L. & Constable C. G., The time-averaged geomagnetic field as recorded by lava flows over the past 5 Myr. Geophys. J. Int., 122 (1995) 489-519.
[20] Carlut J. & Courtillot V., How complex is the time-averaged geomagnetic field over the past 5 Myr? Geophys. J. Int., 134 (1998) 527-544.
[21] Royer J.-Y., Müller R. D., Gahagan L. M., Lawver L. A., Mayes C. L., Nürmer D. & Sclater J. G., A global isochron chart. Techn. Rep. Inst. Geophys. Univ. Texas, 117, (1992).
[22] Müller R. D., Royer J.-Y. & Lawver L. A., Revised plate motions relative to the hotspots from combined Atlantic and Indian Ocean hotspot tracks. Geology, 21 (1993) 275-278.
[23] Morgan W. J., Hotspot tracks and the early rifting of the Atlantic. Tectonophysics, 94 (1983) 123-139.
[24] Watson G. S., A test for randomness. Mon. Not. Roy. Astr. Soc., 7 (1956) 160-161.
[25] Livermore R. A., Vine F. J. & Smith A. G., Plate motions and the geomagnetic field - I. Quaternary and late Tertiary. Geophys. J. R. astr. Soc., 73 (1983) 153-171.

[26] Hargraves R.B., Paleomagnetism of Mesozoic kimberlites in Southern Africa and the Cretaceous apparent polar wander curve for Africa. J. Geophys. Res., 94 (1989), 1851-1866.
[27] Steinberger B. & O'Connell R.J., Advection of plumes in mantle flow : implications for hotspot motion, mantle viscosity and plume distribution. Geophys. J. R. astr. Soc., 132 (1988) 412-434.
[28] Molnar P. & Stock J., Relative motions of hotspots in the Pacific, Atlantic and Indian Oceans since late Cretaceous time. Nature, 327, 587-591
[29] Tarduno J. A. & Gee J., Large-scale motion between Pacific and Atlantic hotspots. Nature, 378, 477-480.
[30] DiVenere V. & Kent D., Are the Pacific and Indo-Atlantic hotspots fixed ? Testing the plate circuit through Antarctica. Earth Plan. Sci. Lett., 170 (1999), 105-117.
[31] Sager W. & Koppers A. A. P., Late Cretaceous polar wander of the Pacific plate : evidence of a rapid true polar wander event. Science, 287, 455-459.
[32] Ricard Y., Spada G. & Sabadini R., Polar wandering of a dynamic earth. Geophys. J. Int., 113 (1993) 284-298.
[33] Richards M. A., Bunge H.-P., Ricard Y. & Baumgardner J.R., Polar wandering in mantle convection models. Geophys. Res. Lett., 26 (1999) 1777-1780.
[34] Ricard Y., Richards M. A., Lithgow-Bertelloni C. & Le Stunff Y., A geodynamic model of mantle density heterogeneity. J. Geophys.Res., 98 (1993) 21895-21909.
[35] Davies G. F., Role of the lithosphere in mantle convection. J. Geophys. Res., 93 (1988) 10451-10466.
[36] Bunge H-P. & Richards M. A., The origin of large scale structure in mantle convection: effects of plate motions and viscosity stratification. Geophys. Res. Lett., 23 (1996) 2987-2990.
[37] Ricard Y., Sabadini R. & Spada G., Isostatic deformations and polar wander induced by redistribution of mass within the Earth. J. Geophys. Res., 97 (1992) 14,223-14,236.
[38] Brunet D. & Machetel P., Large-scale tectonic features induced by mantle avalanches with phase, temperature, and pressure lateral variations of viscosity. J. Geophys. Res, 103 (1998) 4929-4945.
[39] Gallet Y. & Hulot G., Stationary and nonstationary behaviour within the geomagnetic polarity time scale. Geophys. Res. Lett., 24 (1997) 1875-1878.
[40] Gubbins D., Mechanism for geomagnetic polarity reversals. Nature, 326 (1987), 167-169.
[41] Van Fossey M.C. & Kent D. V., Paleomagnetism of 122 Ma plutons in New England and the Mid-Cretaceous paleomagnetic field in North America: true polar wander or large-scale differential mantle motion? . J. Geophys. Res, 97 (1992) 19,651-19,661.
[42] Kirschvink J. L., Ripperdan R. L. & Evans D.A., Evidence for a large-scale reorganization of Early Cambrian continental masses by inertial interchange true polar wander. Science, 277 (1997) 541-545.
[43] Van der Voo R., True polar wander during the middle Paleozoic ? Earth planet. Sci.Lett., 122 (1994) 239-243.
[44] Torsvik T. H., Smethurst M. A., Meert J. G., Van der Voo R., McKerrow W. S., Brasier M. D., Sturt, B. A. & Walderhaug H., Continental break-up and collision in the Neoproterozoic and Palaeozoic : a tale of Baltica and Laurentia. Earth Sci.Rev., 40 (1998) 229-258.
[45] Fisher R. A., Dispersion on a sphere. Proc. R. Soc. London, ser. A, 217 (1953) 295-305.

Table 1. Global paleomagnetic pole positions with respect to the Indo-Atlantic hotspot reference frame for consecutive (non-overlapping) time intervals. N is the number of poles, K the Fisher [45] dispersion parameter, A_{95} the corresponding 95% confidence interval about the mean, and Δ the angular deviation between consecutive poles.

Window	Latitude	Longitude	N	K	A_{95}	Δ
0-10 Ma	86.5	106.4	32	225.8	1.7	-
10-30 Ma	85.2	133.0	16	153.4	3.0	2.3
30-50 Ma	86.2	128.4	7	151.7	4.9	1.1
50-80 Ma	84.6	135.6	20	146.1	2.7	1.7
80-110 Ma	86.2	328.2	8	175.6	4.2	9.1
110-140 Ma	69.2	284.5	12	144.9	3.6	18.2
140-175 Ma	66.8	318.0	7	73.9	7.1	12.6
175-200 Ma	69.1	311.4	16	71.9	4.4	3.4
0-80 Ma	85.8	124.3	75	175.0	1.2	-
140-200 Ma	68.4	313.6	23	73.7	3.5	25.8

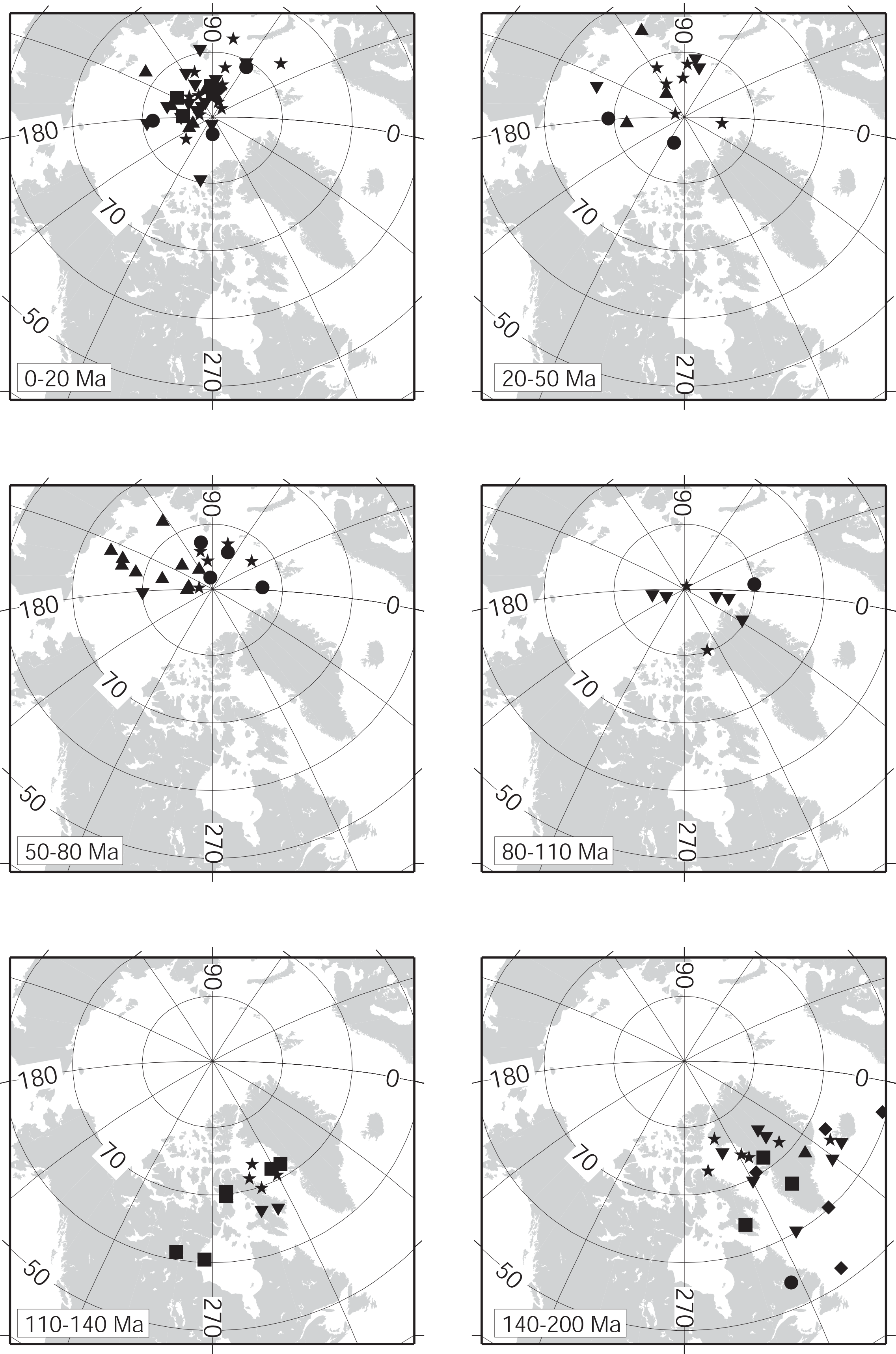
Figure captions

Figure 1. Position of individual palaeomagnetic poles from present to 200 Ma ago after removal of the plate movements relative to the Indo-Atlantic hotspot reference frame. Data from different continents have different symbols: downward pointing triangle (Africa), upward pointing triangles (Eurasia), stars (North America), squares (South America), circles (Australia) and diamonds (East Antarctica). Note the absence of any overlapping in the position of the individual poles before and after the 110 Ma event.

Figure 2. Time-averaged pole positions with respect to the Indo-Atlantic hotspot reference frame as a function of time. **a**: data from the present magmatic database; the mean position and corresponding 95% confidence interval are shown for the four consecutive periods providing distinct positions of the time-averaged poles listed in Table 1. Filled symbols correspond to field model 1 (pure dipole) and empty symbols to field model 3 (dipole plus quadrupole varying with time). **b**: comparison of the pole positions at 10 Ma intervals according to the present magmatic database (filled symbols) and according to the magmatic and sedimentary database of Besse and Courtillot [12] (empty symbols). In the present case the average poles were calculated from non-overlapping 10 Ma wide intervals while overlapping 20 Ma wide intervals were used in [12]. Only two 10 Ma poles (145 and 155Ma) could not be calculated from the magmatic data (see text). Different symbols are used for the consecutive time intervals 0-80 Ma (circles), 80-110 Ma (upward directed triangles), 110-140 Ma (downward directed triangles) and 140-200 Ma (squares).

Figure 3. **a:** Age distribution of the individual poles from the magmatic database for 10 Ma intervals. **b:** Angular deviation of the Earth's rotation axis versus time according to the magmatic palaeomagnetic data (zero set at the pole position averaged over the interval 0-110 Ma; error bars are angular standard deviations *s* of individual pole positions) and according to 3 variants of the dynamic mantle model of Richards et al. [6] (zero set at the actual pole position). In the model, VR is the viscosity ratio from the lower to the upper mantle. Symbols as in Figure 2.

FIGURE 1



90
180
0
70
50
270
0-20 Ma
20-50 Ma
50-80 Ma
80-110 Ma
110-140 Ma
140-200 Ma

FIGURE 2

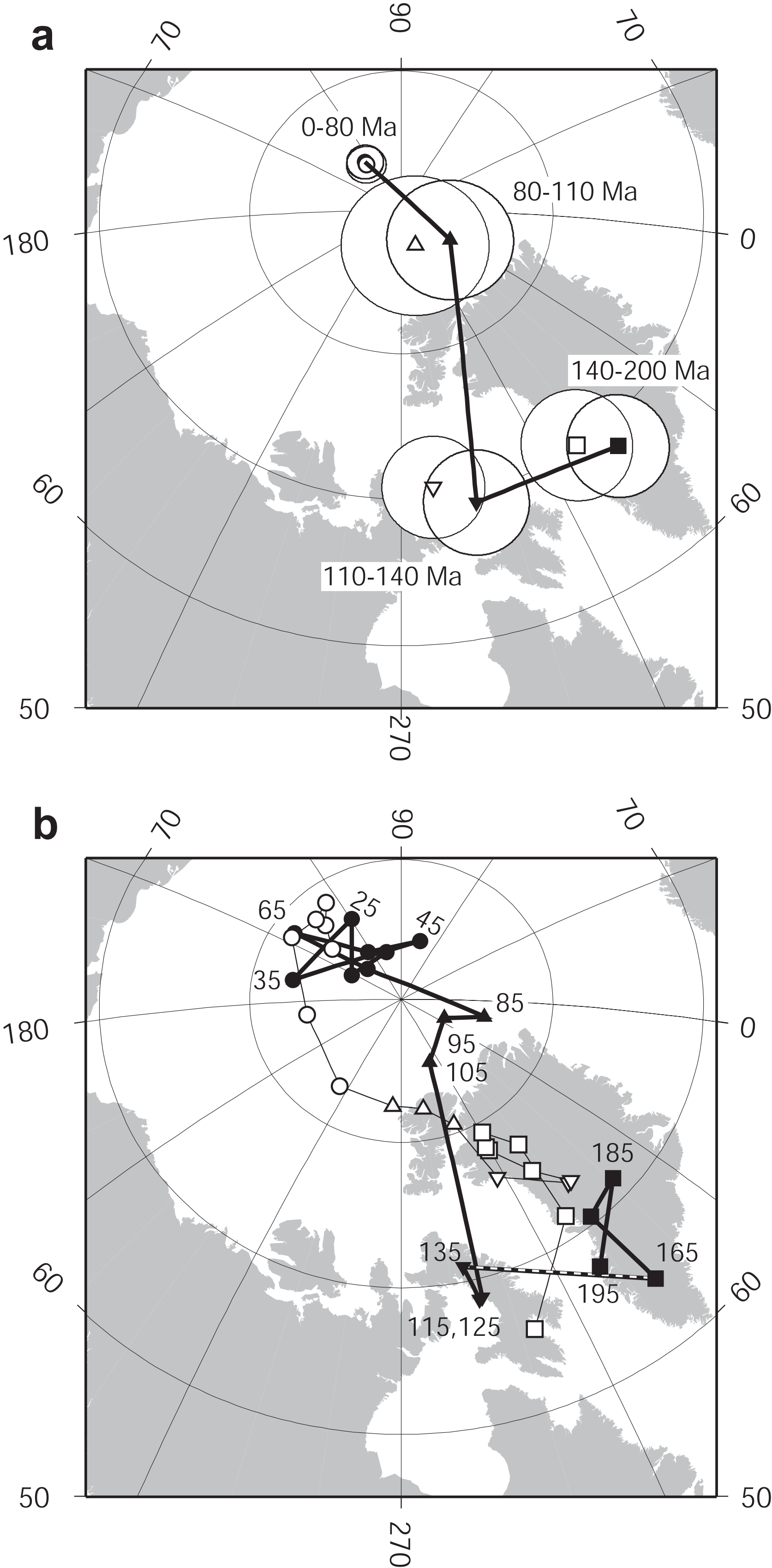
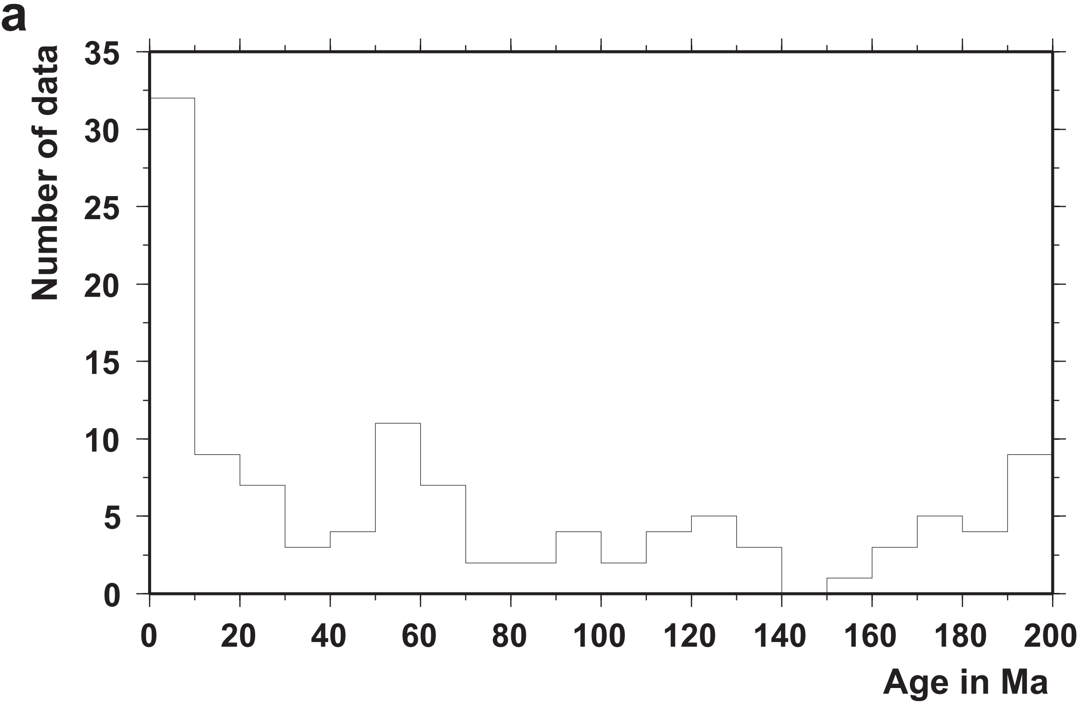
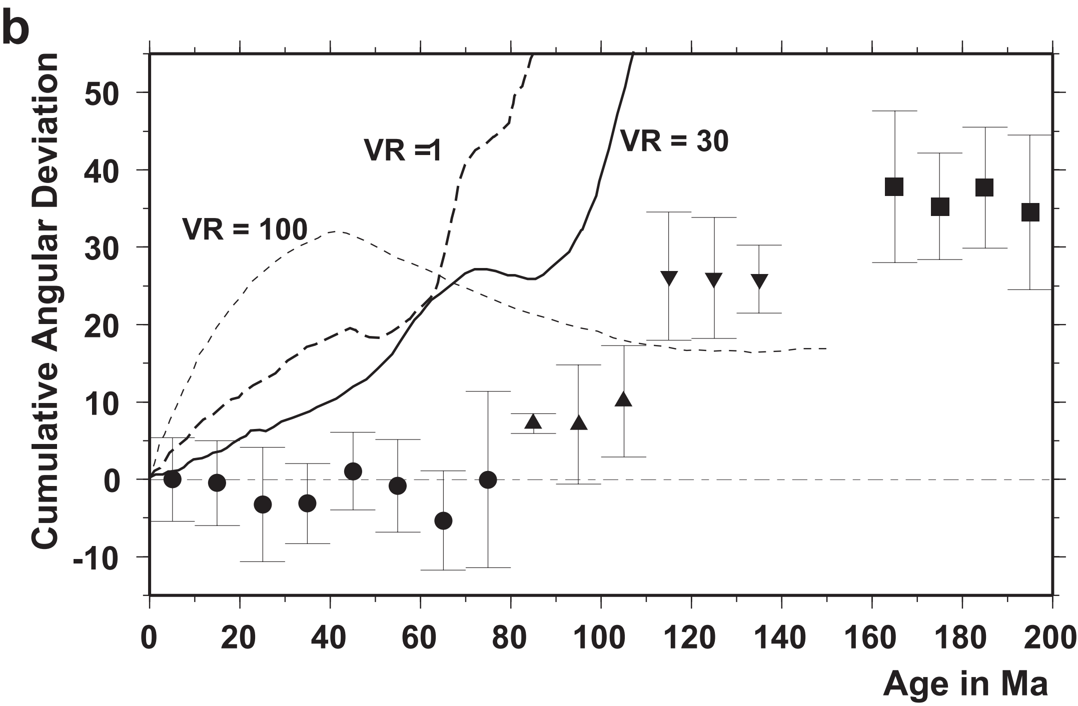

a
90
70
70
0-80 Ma
80-110 Ma
180
0
140-200 Ma
60
60
110-140 Ma
50
50
270
b
90
70
70
65
25
45
35
85
180
0
95
105
185
135
165
195
115,125
60
60
50
50
270

FIGURE 3



a
Number of data
35
30
25
20
15
10
5
0
0 20 40 60 80 100 120 140 160 180 200
Age in Ma



b
Cumulative Angular Deviation
50
40
30
20
10
0
-10
VR =1
VR = 30
VR = 100
0 20 40 60 80 100 120 140 160 180 200
Age in Ma